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Density and viscosity of tight oil from Yanchang Formation, Ordos Basin, China and the geochemical controls

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ABSTRACT
For assessing the density and viscosity of tight oil and their geochemical controls, 47 tight oil samples across the Ordos Basin were analyzed. The oil density and viscosity lay in the ranges of 0.81–0.88 g/ml and 1.9–13.36 mPa·s, which are low in overall. The average saturated hydrocarbon content is higher than 80%. The molecular compositions suggest a source dominated organic matter by lacustrine type I/II with minor input of terrestrial type III kerogen. The oils were mainly generated at relatively high maturities. Fractionation during the oil expulsion may also result in the depletion of heavy-ends compounds. These are the main controlling factors for the overall good quality of the Ordos tight oil.

KEYWORDS
density and viscosity; geochemical characteristics; maturity; Ordos Basin; organic matter type; tight oil

1. Introduction

'Tight oil' is the oil present in low-permeability shale and sandstone/carbonate interbedded with source rocks (EIA 2013). Great success in tight oil exploration and production in the U.S. has encouraged tight oil exploration in China (Yang, Li, and Liu 2016). The Triassic Yanchang Formation in the Ordos Basin is one of the most promising tight-oil-producing areas in China (Yang, Li, and Liu 2016). Numerous studies have been performed on the mineral composition, diagenesis, porosity and permeability of tight sandstone reservoirs (Zhou et al. 2016; Li, et al. 2017). However, the characteristics of oil from the tight sandstone have not been investigated on a basin scale.

Physical properties of tight oil such as density and viscosity play critical roles in migration, and are closely related to chemical composition of tight oil. Oil containing more gaseous (C_{1-5}) and light (C_{6-20}) hydrocarbons has lower density and viscosity than oil rich in C_{20+} compounds (Werner et al. 1998). The chemical composition of oil is primarily regulated by the type and depositional environment of source organic matter (Tissot and Welte 1984). Oil originated from marine organic matter generally has a higher content of aromatic hydrocarbons and polar compounds than that is associated with non-marine organic matter. Primary migration of oil leads to a preferential retention of polar compounds rather than hydrocarbons in source beds. Thermal evolution also decreases the amount of polar compounds in oil and increases the light-end hydrocarbons at the same time.

The Ordos Basin is one of the most important petroliferous basins in China. Oil produced in the basin is almost sourced from the seventh Member (Chang7) of the Triassic Yanchang Formation, and the reservoirs in the sixth and seventh Members (Chang6 and Chang7) are mainly ultra-low-permeability sandstones (0.02 to 0.41 md). In this study, 47 tight oil samples were collected from several typical oil

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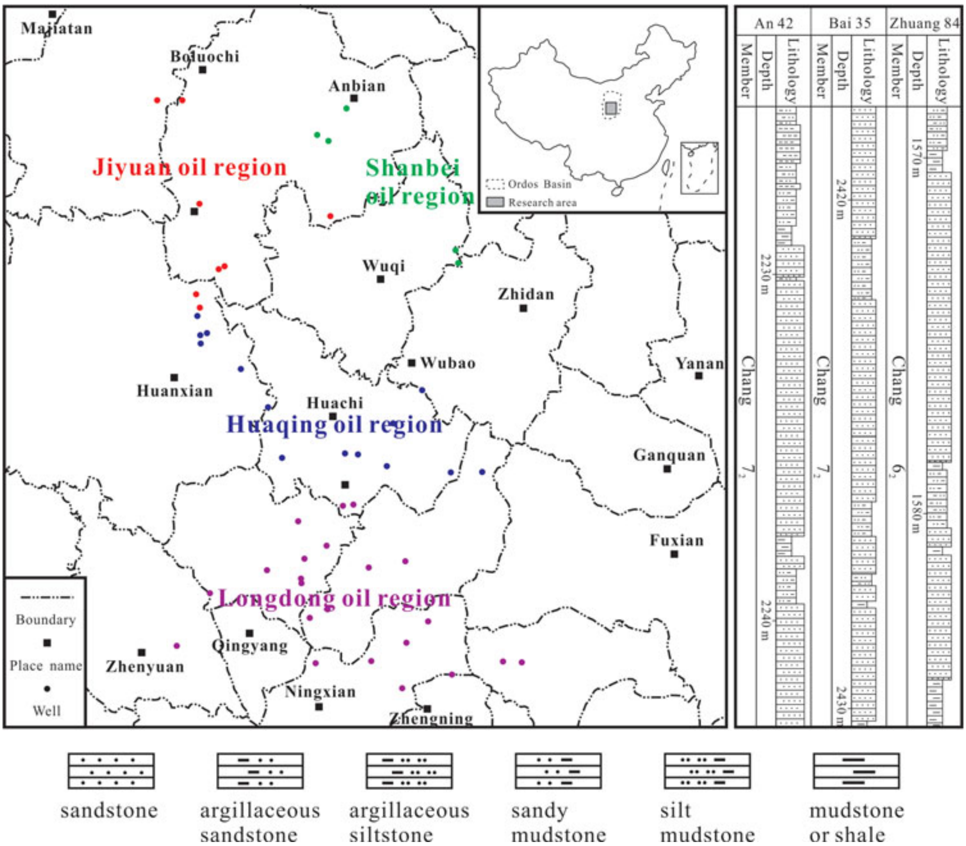

Figure 1. Sketch map showing sampling locations and stratigraphic columns of three typical wells showing three main tight sandstone formations.

fields across the Ordos Basin including Jiyuan, Shanbei, Huaqing and Longdong regions, respectively (Figure 1, Table 1). The chemical compositions, including both oil fraction content and molecular characteristics, were obtained to understand the main geochemical factors influencing the physical properties of tight oil.

2. Samples and experiments

2.1. Experiments

Oil density and viscosity were measured using a DMA™ 4500 M automatic densitometer and a MCR 101 rheometer (both Anton-Paar GmbH), respectively. About 20–30 mg of the oil sample was subject to column chromatography on silica gel (80–100 mesh)/Al_2O_3 (100–200 mesh) after the precipitation of asphaltenes. The saturated hydrocarbons, aromatic hydrocarbons and resins were eluted with *n*-hexane, *n*-hexane:dichloromethane (3:2, v:v) and methanol, respectively. The saturated hydrocarbons and aromatic hydrocarbons were analyzed using a Thermo Electron Corporation DSQ II mass spectrometer coupled to a Trace™ gas chromatograph equipped with a DB-5MS column (30 m × 0.32 mm × 0.25 μm) to determine molecular compositions.

3. Results

3.1. Physical properties

The tight oil samples from the Chang6 and Chang7 Members generally has relatively low density and low viscosity, in the ranges 0.81–0.88 g/ml and 1.9–13.36 mPa·s, averaging 0.83 g/ml and 4.68 mPa·s,

Table 1. Statistical data of tight oil samples showing the physical and geochemical characteristics.

Member		Density (g/ml)	Viscosity (50°C mPa·s)	Sat. (%)	Aro. (%)	Res.+Asp. (%)	nC_{20-}/nC_{21+}	CPI	Pr/nC_{17}	Ph/nC_{18}	C_{29} $\beta\beta/(\alpha\alpha+\beta\beta)$	C_{29} S/(S+R)	$C_{30}^*/C_{30}H$	MPI	R_c (%)
Chang6 ($n = 10$)	Min.	0.81	1.90	79.20	5.19	2.57	1.21	1.05	0.17	0.19	0.60	0.44	0.04	0.86	0.91
	Max.	0.84	7.45	89.84	8.94	14.79	1.80	1.27	0.48	0.73	0.65	0.59	0.74	1.54	1.32
	Avg.	0.82	3.29	84.92	7.05	8.03	1.53	1.14	0.26	0.37	0.63	0.52	0.21	1.08	1.04
Chang7 ($n = 37$)	Min.	0.81	1.96	66.64	4.36	1.26	1.02	1.00	0.11	0.11	0.45	0.39	0.04	0.75	0.85
	Max.	0.88	13.36	94.38	16.27	27.05	1.70	1.26	0.59	1.18	0.71	0.57	4.04	1.30	1.18
	Avg.	0.83	5.06	80.27	10.08	9.65	1.42	1.09	0.31	0.43	0.62	0.51	0.58	0.92	0.94

Abbreviations: Sat. = Saturated hydrocarbons; Aro. = Aromatic hydrocarbons; Res. = Resins; Asp. = Asphaltenes; C_{29} $\beta\beta/(\alpha\alpha+\beta\beta)$ = C_{29} $\alpha\beta\beta/(\alpha\alpha\alpha+\alpha\beta\beta)$ sterane; C_{29} S/(S+R) = C_{29} 20S/(20S+20R) sterane; $C_{30}^*/C_{30}H$ = C_{30} diahopane/hopane; MPI = 1.5 * (3-MP + 2-MP)/(P + 9-MP +1-MP); R_c = 0.6 * MPI + 0.4; P and MP refer to phenanthrene and methyl phenanthrene.

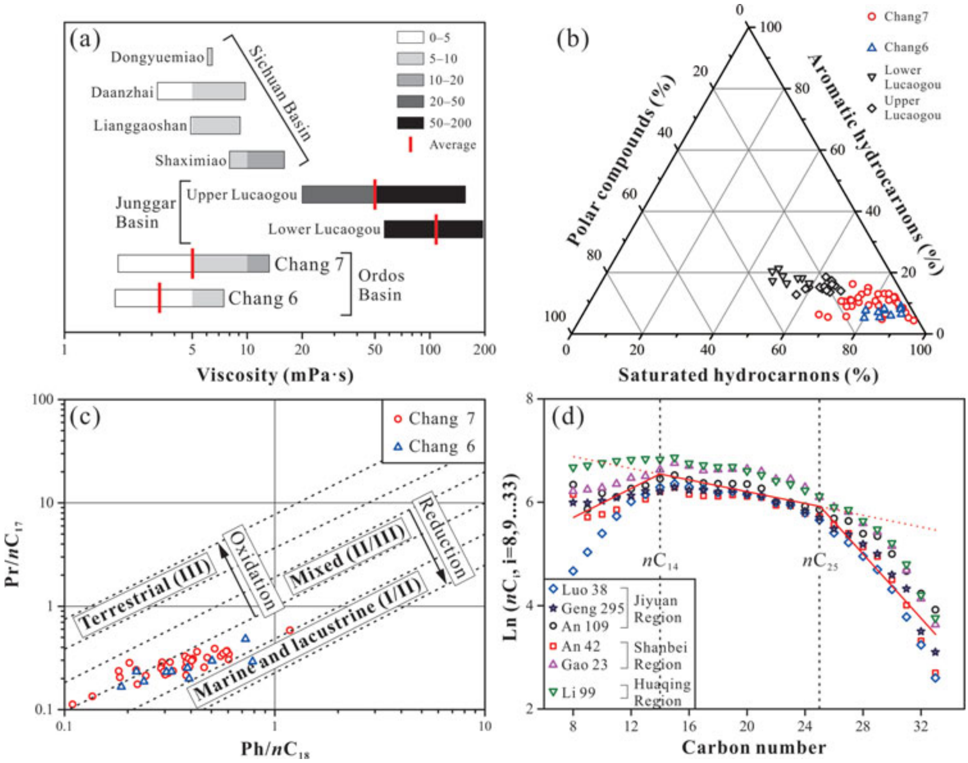

Figure 2. (a) Ranges and average values of viscosity for tight oil from three typical basins in China. (b) Ternary diagram showing fractional compositions of tight oil samples from the Yanchang Formation, Ordos Basin and Lucaogou Formation, Junggar Basin. (c) Cross-plots of Pr/nC_{17} vs. Ph /nC_{18} ratios for tight oil samples. (d) Distributions of relative amounts of *n*-alkanes with different carbon numbers for six typical tight oil samples. Data for Junggar and Sichuan Basins is from Cao et al. (2017) and Li et al. (2017), respectively.

respectively (Table 1), with slightly lower density and viscosity in the Chang6 Member. Physical and geochemical characteristics have been reported for tight oil from the Junggar and Sichuan Basins (Cao et al. 2017; Li et al. 2017), which are also very important basins for tight oil potential in China (Jia et al. 2016). The density of Yanchang tight oil from the Ordos Basin is roughly similar to that from the Sichuan Basin, but lower than the density of oil from the Junggar Basin. The viscosity of the Yanchang oil is slightly lower than that from the Sichuan Basin, and significantly lower than that from the Junggar Basin (Figure 2(a)).

3.2. Geochemical characteristics

3.2.1. Fractional compositions

The extremely low asphaltene content of the tight oil appears in combination with the resin content (Table 1). The saturated hydrocarbon content is notably high (66.64–94.38%, average 81.26%). The aromatic hydrocarbon and polar compound contents are around 4.36–16.27% and 1.26–27.05%, averaging 9.44% and 9.31%, respectively (Figure 2(b); Table 1). In addition, the average saturated hydrocarbon content of oils from the Chang6 Member (84.92%) is greater than that from the Chang7 Member; however, the aromatic and polar contents show the opposite trend. As a result, the average ratio of saturated to aromatic hydrocarbons is greater for the Chang6 oil (12.39) than for the Chang7 oil (8.96).

3.2.2. Saturates and aromatics

Typical distributions of saturated and aromatic hydrocarbons in tight oil from the Yanchang Formation (Figure 3) were generally similar. The saturated hydrocarbons are dominated by C_{10-35} *n*-alkanes, with relatively low branched or naphthenic hydrocarbons. The distribution of *n*-alkanes shows a unimodal

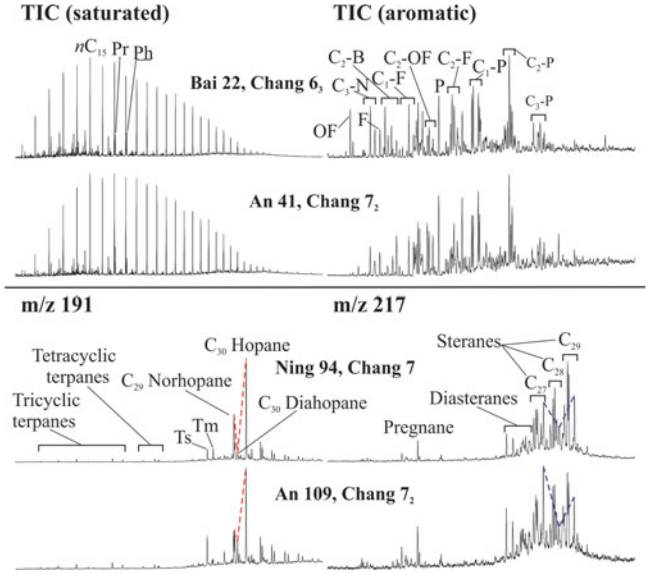

Figure 3. Total ion current (TIC) chromatograms of saturated and aromatic hydrocarbons, and mass chromatograms of *m/z* 191 and 217 showing the distribution of terpanes and steranes in four typical oil samples. Abbreviations: Pr = pristane; Ph = phytane; OF = dibenzofuran; F = fluorene; P = phenanthrene; N = naphthalene; B = biphenyl. Label with C_i- prefix (i = 1, 2, 3) is methyl substitute of the aromatic hydrocarbon, and "i" represents the number of methyl.

pattern peaking at C_{15}–C_{19}, such that the n-C_{20-} /n-C_{21+} value mainly varies from 1.41 to 2.67, which suggests a predominance of short-chain hydrocarbons (Table 1). The CPI of tight oil samples ranges 1.00–1.27, suggesting a relatively high thermal evolution level (Peters, Walters, and Moldowan 2005). The Pr/n-C_{17} and Ph/n-C_{18} are about 0.25–0.59 and 0.38–1.18, respectively (Table 1).

Major aromatic compounds identified in the tight oil include naphthalene, biphenyl, phenanthrene, fluorene, dibenzofuran and their methyl substitutes, among which phenanthrene series are slightly more abundant (Figure 3). By contrast, compounds with more than three aromatic rings (e.g. pyrene, chrysene and perylene) were seldom detected, implying limited terrestrial high plants in the source matrix (Aizenshtat 1973).

3.2.3. Biomarkers

Most samples contained abundant pentacyclic triterpanes and a small amount of tricyclic triterpanes (Figure 3), suggesting a major contribution from lower aquatic organisms (Peters, Walters, and Moldowan 2005). Regular steranes, diasteranes and some pregnanes were widely detected. The relative amounts of regular steranes vary, in descending order, from C_{27} sterane, C_{29} sterane to C_{28} sterane (Figure 3). The relative abundance of C_{30} diahopane and diasteranes varied greatly between samples. Generally, tight oils from the Chang7 Member showed wider ranges of the C_{30} diahopane/hopane and diasterane/sterane ratios (Table 1).

4. Discussion

4.1. Source characteristics of tight oil

The Pr/n-C_{17} and Ph/n-C_{18} ratios were widely used to study the organic matter type, depositional environment and maturity of oil (Peters, Walters, and Moldowan 2005). The ranges of two ratios from most samples suggest that these oils were mainly derived from heterogeneous lacustrine source material deposited in a relatively reducing environment (Figure 2(c)), with support from the relatively high n-C_{20-}/n-C_{21+} ratio. However, the relatively large variations in these ratios also suggest possible influences from thermal maturity.

As stated above, the collected oils showed large variations in the relative abundance of C_{30} diahopane and diasteranes, and the C_{30} diahopane/hopane ratio varied by more than two orders of magnitude (0.03–6). It has been shown that the relative abundance of C_{30} diahopane and sterane mainly reflect variation in the redox conditions and exist of clay minerals, besides in the organic type and maturity (Peters, Walters, and Moldowan 2005). Therefore, relative amounts of diahopane and diasteranes in the tight oil indicate variations in depositional environment of the source organic matter, such as water depth of the lake.

4.2. Maturity

C_{29} $\alpha\beta\beta/(\alpha\alpha\alpha+\alpha\beta\beta)$ sterane and C_{29} 20S/(20S+20R) sterane ratios of tight oil lie in the ranges 0.45–0.71 and 0.39–0.59, respectively (Table 1), approaching or having reached equilibrium, suggesting most of samples were in the peak oil generation stage (Peters, Walters, and Moldowan 2005). The methyl phenanthrene index (MPI) is another widely used maturity parameter, and the equivalent vitrinite reflectance (R_c) calculated with MPI (Radke and Welte 1983) mainly ranges from 0.85% to 1.20% (mean 0.97%; Table 1), suggesting a maturity range from oil peak to late oil-generation stage.

4.3. Fractionation during oil expulsion

The relative amount of *n*-alkane in initial oil without any secondary alteration exhibits an exponential relationship with carbon number (Kissin 1987). As shown in Figure 2(d), the relative amounts of light ($< C_{14}$) and heavy *n*-alkanes ($> C_{25}$) are obviously lower than expected. This abnormal phenomenon for light alkanes may be attributed to evaporative loss. The depletion of heavy *n*-alkanes might be resulted from compositional fractionation induced by the migration of oil from the source layer to the tight sandstone, since heavy *n*-alkanes are preferentially retained by the source layer. Generally, the organic classes in source layer have retention preference: saturated hydrocarbons < aromatic hydrocarbons < resins < asphaltenes (Ritter 2003). In addition to the influence of thermal maturity, very high saturated/aromatic hydrocarbons ratio in the tight oil may also be caused by composition fractionation during oil expulsion.

4.4. Geochemical effects on the physical properties of tight oil

The tight oil from the Yanchang Formation exhibited much lower oil density, viscosity and polar compound content than that from the Lucaogou Formation, Junggar Basin (Figure 2(a), (b)), but a higher ratio of saturated/aromatic hydrocarbons. The Yanchang Formation tight oils are dominated by short-chain *n*-alkanes (Figure 3), which differs from Lucaogou Formation oils that generally contain very abundant long-chain *n*-alkanes and biomarkers (Cao et al. 2017). In addition, the detection of a high relative amount of β-carotane in the Lucaogou tight oil suggests a saline lake depositional environment (Cao et al. 2017). However, such evidence was not found in the tight oil from the Yanchang Formation. Although both the Lucaogou and Yanchang Formation source rocks are mainly composed of type I/II, terrestrial higher plants may have contributed a relatively large proportion to the organic material in the Lucaogou Formation. The differences in depositional environment and organism inputs could thus account for the differences in the polar and aromatic content in tight oils from the two formations.

Maturity has another critical effect on the physical properties of tight oil. The C_{29} $\alpha\beta\beta/(\alpha\alpha\alpha+\alpha\beta\beta)$ sterane and C_{29} 20S/(20S+20R) sterane ratios of tight oil from the Lucaogou Formation (0.20–0.35 and 0.25–0.48, respectively) are notably lower than those from the Yanchang Formation. Moreover, the Pr/n-C_{17} and Ph/n-C_{18} ratios of the Lucaogou tight oil (0.8–1.9 and 0.6–3.3, respectively) are much higher than those of the tight oil in this study (Figure 2(c)), indicating overall lower maturity. With increasing maturity, the average amount of aromatic hydrocarbons and polar compounds has generally decreased, resulting in lower oil density and viscosity.

The oil expulsion-related fraction may further augment the relative amount of saturated hydrocarbons and light-end alkanes in the tight oil from the Yanchang Formation, which may have further facilitated a reduction in oil viscosity. However, the predominance of heavy-end alkanes in the Lucaogou oil seems to suggest this effect could not be properly evaluated.

5. Conclusions

The tight oil samples from the Chang6 and Chang7 Members of the Yanchang Formation, Ordos Basin show overall low density and viscosity. It is closely related to a very high saturated hydrocarbon content and low aromatic hydrocarbon content, along with minor heavy polar compounds in the oil. Tight oils were mainly derived from lacustrine type I/II organic matter with minor contributions from terrestrial higher plants, and generally they were generated at a relatively high maturity stage. These two geochemical factors are responsible for the physical and compositional characteristics of the tight oil from the Yanchang Formation. Compositional fractionation during oil expulsion may lead to increasing the light-end components of the oil, thus improving its overall quality.

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